

**METHOD AND APPARATUS  
FOR LEAK TESTING AN ENVIRONMENTAL ENCLOSURE**

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***CROSS-REFERENCE TO RELATED APPLICATION***

The present application claims the benefit of U.S. provisional application No. 60/421,593, filed October 24, 2002.

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***FIELD***

The present disclosure concerns a method and apparatus for leak testing an environmental enclosure used in a polluted atmosphere, such as an operator cab of a vehicle.

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***BACKGROUND***

Vehicles used in polluted atmospheres, such as those used in mining or agricultural work, are equipped with air filtration equipment for protecting the operators of such equipment from airborne contaminants. Such vehicles typically have an enclosed operator cab and a ventilation system having an air inflow conduit for feeding a motor-driven fan or blower. The fan induces air to flow through a dust filter and in some installations, an activated-charcoal filter for adsorbing harmful vapors/gases, after which the filtered air is conveyed into the operator cab.

Enclosed operator cabs can provide very high levels of protection from airborne contaminants so long as clean, filtered air is introduced into the cab with positive air pressurization of the cab interior. However, leaks in the ventilation system can allow airborne contaminants to enter the operator cab. Typically, the areas within a ventilation system that have a tendency to cause leaks include the sealing area around the filter, the joints between separate portions of ductwork, and the openings in the ductwork provided for the electrical wiring of the fans. If major leaks occur, the effectiveness of the cab filtration system can be severely diminished, thereby compromising the safety of the operator. Thus, the ventilation

system should be periodically leak tested to ensure the cab enclosure provides sufficient protection for the operator.

One method for leak testing the ventilation system of a cab enclosure is specified in ASAE (American Society of Agricultural Engineers) Standard S525. In this method, the vehicle being tested is driven over a non-paved surface to increase the levels of aerosol and dust in the atmosphere surrounding the vehicle. As the vehicle is driven, one optical particle counter is used to measure ambient aerosol and dust concentrations outside the operator cab of the vehicle and another optical particle counter is used to measure aerosol and dust concentrations inside the operator cab. For a cab to be considered acceptable, the ratio of the concentrations outside the cab to the concentrations inside the cab must be greater than 50. Heitbrink et al., "Review of Ambient Aerosol Test Procedures in ASAE Standard S525," *Journal of Agricultural Safety and Health*, 4(4): 255-266 (1998).

The foregoing method suffers from the drawback that the concentration of ambient aerosols varies with location and time of year. Thus, the test can be impractical in certain locations or during certain times of the year when the ambient aerosol concentration is not large enough to overcome any extraneous aerosol generation in the cab. *Id.*

In another method for leak testing the ventilation system of an operator cab, the cab is placed inside a laboratory test chamber and exposed to an atmosphere containing a constant level of ethyl acetate. During the test, the ventilation system of the cab is operated to cause the surrounding atmosphere to flow through a filter capable of filtering ethyl acetate and into the interior of the cab. A gas monitor placed inside the cab is used to detect for the presence of leaks in the ventilation system by monitoring the concentration of ethyl acetate inside the cab. Although more reliable than the method for testing cabs in the field set forth by ASAE Standard S525, laboratory testing is much more inconvenient than such field-testing since the cab to be tested must be driven or otherwise transported to a testing facility.

Accordingly, there exists a need for new and improved systems for leak testing ventilation systems of enclosed operator cabs.

*SUMMARY*

According to one aspect, methods are provided for leak testing the ventilation system of an environmental enclosure using a gas that is naturally present in ambient air (e.g., nitrogen, oxygen, argon, or carbon dioxide) as a tracer gas. An  
5 embodiment of such a method includes inducing outside air to flow through a filter in the ventilation system and into the enclosure so as to establish positive pressurization inside the enclosure. The filter includes filter media selected to filter tracer gas from the air stream flowing through the filter to cause a decrease in the concentration of tracer gas inside the enclosure. During the test, the concentration of  
10 tracer gas inside the enclosure is monitored to determine the lowest achievable concentration of tracer inside the enclosure.

To determine whether there are any leaks in the ventilation system, the lowest achievable concentration of tracer gas inside the enclosure is compared to the expected concentration of tracer gas inside the enclosure due to losses through the  
15 filter. The presence of leaks in the ventilation system is revealed if the lowest achievable concentration of tracer gas is greater than the expected concentration of tracer gas inside the enclosure due to losses through the filter.

Desirably, the filter is designed to be 100% efficient; that is, the filter is capable of removing all of the tracer gas from the air flowing through the filter.  
20 Using such a filter, the presence of leaks is revealed if the lowest achievable concentration of tracer gas is greater than zero.

In a disclosed embodiment, carbon dioxide that is naturally present in the ambient air is used as the tracer gas for leak testing an enclosure. Hence, in this embodiment, the filter media is selected to filter carbon dioxide from the air stream  
25 flowing through the filter. In particular embodiments, for example, soda lime is used as the filter media for absorbing carbon dioxide from the air flowing through the filter. However, various other types of filter media, such as sodium hydroxide, calcium hydroxide or lithium hydroxide, also may be used.

The use of a naturally-occurring component of air as a tracer gas for leak  
30 testing an enclosure, such as described above, provides several advantages. In particular, vehicles can be easily tested in the field, without the need for an expensive or elaborate test chamber, since the tracer gas is naturally present in the

atmosphere surrounding the vehicle to be tested. Moreover, such field-testing requires only the use of a single monitoring device, which is used for measuring the concentration of the tracer gas inside the enclosure being tested. In contrast, the test procedure specified by ASAE Standard S525 requires a particle counter for  
5 monitoring particle concentrations outside the enclosure being tested and another particle counter for monitoring particle concentrations inside the enclosure. Further, using a component of air as the tracer gas eliminates the constraints associated with using ambient aerosols and dust for testing an enclosure, such as specified by ASAE Standard S525.

10 The foregoing and other features and advantages of the invention will become more apparent from the following detailed description of several embodiments, which proceeds with reference to the accompanying figures.

### ***BRIEF DESCRIPTION OF THE DRAWINGS***

15 FIG. 1 is a schematic side view of an enclosed operator cab of a vehicle.

FIG. 2 is a perspective view of a filter, according to one embodiment, configured to fit in the ventilation system of an operator cab for the purpose of leak testing the ventilation system.

20 FIG. 3 is an enlarged cross-sectional view of the filter of FIG. 2 taken along line 3-3 in Fig. 2.

FIG. 4 is a perspective view of a filter, according to another embodiment, configured to fit in the ventilation system of an operator cab for the purpose of leak testing the ventilation system.

25 FIG. 5 is a cross-sectional view of the filter of FIG. 4, taken along a plane perpendicular to the longitudinal axis of the filter.

### ***DETAILED DESCRIPTION***

FIG. 1 illustrates a method, according to one embodiment, for leak testing the ventilation system 10 of an environmental enclosure, such as the illustrated  
30 enclosed vehicle operator cab 12, using a gas that is naturally present in ambient air (e.g., nitrogen, oxygen, argon, or carbon dioxide) as a tracer gas. For the purpose of testing the ventilation system 10, the existing filter of the vehicle is temporarily

removed and replaced with a test filter, indicated at 16, capable of filtering the tracer gas from the air flowing through the filter 16. The test filter 16 desirably is 100% efficient; that is, the filter 16 is capable of removing all of the tracer gas from the air flowing through the filter.

5           The ventilation system 10 includes ductwork 14 defining an inlet conduit 20 and one or more airflow inducers 18 (e.g., fans or blowers). The inducers 18 are operable to induce outside air to flow through the inlet conduit 20 and the filter 16, and into the cab 12 through an opening 22, as indicated by arrows A.

10           The operator cab 12 can be the operator cab of any of various types of equipment, such as, without limitation, industrial and agricultural equipment, such as trucks, front-end loaders, tractors, drilling machines, bulldozers, pan-scrapers, draglines, and excavators or military vehicles, such as tanks. In addition, the methods and apparatus disclosed herein can also be applied to various other types of environmental enclosures, such as rooms or buildings equipped with filtration  
15           equipment to prevent the ingress of outside contaminants (e.g., clean rooms used in semiconductor or pharmaceutical manufacturing).

20           The filter 16 contains filter media selected to filter the tracer gas from the air flowing through the filter 16. In a specific approach, for example, carbon dioxide that is naturally present in the ambient air surrounding the cab 12 is used as the tracer gas. Hence, in this approach, any of various chemical absorbents, such as soda lime, sodium hydroxide, calcium hydroxide or lithium hydroxide, can be used as filter media in the filter 16 for filtering carbon dioxide from the ambient air. Further details of a filter 16 for filtering carbon dioxide from air are described below in connection with FIGS. 2 and 3.

25           To determine whether there are any leaks in the ventilation system 10, the inducers 18 are activated to induce outside air to flow through the ventilation system 10 and into the cab 12 to establish positive pressurization inside the cab 12. A suitable gas monitor, indicated at 24, is used to monitor the concentration of the tracer gas inside the cab 12 during the test. Initially, the concentration of the tracer  
30           gas inside the cab 12 is approximately the same as the concentration of the tracer gas in the ambient air outside the cab 12. As filtered air depleted in the tracer gas flows into the cab 12, the concentration of the tracer gas inside the cab 12 decreases. The

test is carried out until the concentration of the tracer gas inside the cab 12 reaches a minimum level at or above zero. Since the filter 16 in this embodiment is 100% efficient, the concentration of the tracer gas inside the cab 12 will be reduced to zero if there are no leaks in the ventilation system 10. However, the presence of leaks in  
5 the ventilation system 10 is revealed if the concentration of the tracer gas inside the cab 12 is reduced to a minimum level greater than zero.

If it is determined that there are leaks in the ventilation system 10, then further tests can be performed to identify the exact locations of such leaks. In one approach, for example, leaks are identified by flowing tracer gas from a pressurized  
10 source of such tracer gas (e.g., a gas cylinder filled with a charge of the tracer gas) over the external surface areas of the ventilation system 10 that could be contributing to the leaks while monitoring the concentration of the tracer gas inside the cab 12. Typically, such areas of the ventilation system 10 that have a tendency to cause leaks include the sealing area around the filter 16, the joints between  
15 separate portions of ductwork 14, and the openings in the ductwork 14 provided for the electrical wiring of the inducers 18. If a leak exists in a specific area of the ventilation system 10, then there will be a sudden increase in the concentration of the tracer gas measured inside the cab 12 as tracer gas is flowed over that area. Once the leaks are identified, appropriate steps can be taken to repair and/or replace  
20 the components of the ventilation system 10 causing the leaks.

Although the filter 16 is described as having an efficiency of 100%, this is not a requirement. Accordingly, filters having efficiencies less than 100% also may be used to perform a leak-test on the ventilation system 10. In one approach, for example, the concentration of the tracer gas in the ambient air outside the cab 12 is  
25 measured with the monitor 24 to determine the expected concentration of tracer gas inside the cab 12 due to losses through the filter. The cab 12 is then pressurized in the manner described above to determine the lowest achievable concentration of tracer gas inside the cab 12, which is then compared to the expected concentration of tracer gas inside the cab due to losses through the filter. The presence of leaks in the  
30 ventilation system 10 is revealed if the lowest achievable concentration of tracer gas inside the cab is greater than the expected concentration of tracer gas due to losses through the filter.

For example, if the concentration of carbon dioxide in the atmosphere surrounding the cab 12 is 400 ppm and the filter 16 is designed to remove 98% of the carbon dioxide from air flowing through the filter, the expected concentration of carbon dioxide inside the cab 12 due to losses through the filter is 8 ppm ( $.02 \cdot 400$  ppm). Thus, for this example, the presence of leaks in the ventilation system 10 is revealed if the lowest achievable concentration of carbon dioxide inside the cab 12 is greater than 8 ppm.

Referring to FIGS 2 and 3, there is shown a test filter 16, according to one embodiment, configured to filter carbon dioxide from ambient air flowing through the filter. As shown, the filter 16 in the illustrated configuration has a generally rectangular filter housing 30, with filter media 38 contained within the housing 30. Air enters the filter 16 from the air inlet side on the back, or hidden, side of the air filter 16 as illustrated in FIG. 2. After passing through the air filter 16, filtered air depleted in carbon dioxide exists from the air outlet side 32, flowing in general in the direction of the arrows in FIGS. 2 and 3.

As best illustrated in FIG. 3, the filter 16 includes an inlet-side fibrous electrostatic filter element 34 and an outlet-side fibrous electrostatic filter element 36, although other types of filter elements also may be used. The space between the filter elements 34 and 36 is packed with filter media 38 capable of filtering carbon dioxide from the air flowing through the filter. In particular embodiments, the filter media 38 is a chemical absorbent, such as soda lime, sodium hydroxide, calcium hydroxide or lithium hydroxide, for absorbing carbon dioxide from the air flowing through the filter 16. Filter elements 34 and 36 serve to trap airborne particulate matter and retain the filter media 38 within the housing 30. A gasket 40 surrounding the periphery of the outlet side 32 serves to seal the filter 16 inside the ventilation system.

Since the sealing area around the periphery of the existing filter of the cab is a common source of leaks, the housing 30 of the test filter 16 desirably has the same overall dimensions as the existing filter of the enclosure to be tested. Also, a gasket that is identical to the existing gasket desirably is used with the test filter 16. In this manner, the integrity of the gasket design and the interface area between the existing filter and the surrounding ductwork 14 is tested in a leak-test of the ventilation

system 10. Alternatively, if desired, the existing gasket of the ventilation system may be used with the test filter 16.

The construction of the filter 16 is not limited to that of the illustrated embodiment. In alternative embodiments, for example, the housing 30 of the filter 16 may be cylindrical in shape or have any of various geometric shapes. In addition, reference is made to U.S. Patent No. 5,423,903 to Schmitz et al., which discloses an activated charcoal filter for an operator cab. The filter in the '903 patent can be adapted to filter carbon dioxide from an air stream by replacing the activated charcoal with soda lime or other suitable absorbent materials.

If a component of air other than carbon dioxide is used as the tracer gas to leak-test the ventilation system 10, then the filter media 38 is selected for filtering that component from the stream of air passing through the filter. For example, if oxygen or nitrogen is used as the tracer gas, the filter media 38 may comprise a molecular sieve selected to adsorb either oxygen or nitrogen from the air stream passing through the filter.

Referring to FIGS. 4 and 5, a carbon dioxide filter according to another embodiment is indicated generally at 50. The filter 50 in the illustrated configuration is generally cylindrical in shape and has an outer metal screen 52, an outer or inlet side filter element 54, an inner or outlet side filter element 56, and filter media 58 (e.g., soda lime) interposed between the filter elements 54 and 56. Filter element 54 in the illustrated form is a pleated style filter element, although this is not required. Air enters the filter 50 through the screen 52, flows through filter element 54, filter media 58, filter element 56, and exits the filter through an outlet 60, in the direction of the arrows in FIG. 4.

The relationship between airflow into an enclosure, such as the illustrated cab 12, and the concentration of the tracer gas inside the enclosure over a test period can be described by the vapor/gas decay equation

$$Vdx = Q_g dt - Qxdt, \quad (1)$$

where  $V$  is the volume of the enclosure,  $x$  is the concentration of the tracer gas inside the enclosure,  $Q_g$  is the volumetric inflow rate of tracer gas into the enclosure,  $Q$  is



the total volumetric flow rate of air through the ventilation system (including filtered and leaked gas), and  $t$  is time. Hartman, H. L., MINE VENTILATION AND AIR CONDITIONING, 1961, p. 398.

Rearranging equation 1 for integration yields:

$$5 \quad \int_{x_o}^x \frac{dx}{Q_g - Qx} = \frac{1}{V} \int_{t_o}^t dt. \quad (2)$$

Solving equation 2 yields:

$$\ln \frac{Q_g - Qx}{Q_g - Qx_o} = -\frac{Q\Delta t}{V}. \quad (3)$$

Substituting  $Qlc$  for gas leakage  $Q_g$  into the cab, where  $l$  is the percent leakage of outside air around and/or through the ventilation system, and  $c$  is the concentration of the tracer gas outside the enclosure (in percent by volume), equation 3 becomes

$$10 \quad \ln \frac{Qlc - Qx}{Qlc - Qx_o} = -\frac{Q\Delta t}{V}. \quad (4)$$

Simplifying equation 4 yields:

$$\ln \frac{lc - x}{lc - x_o} = -\frac{Q\Delta t}{V}. \quad (5)$$

Solving equation 5 for  $\Delta t$  produces the equation

$$15 \quad \Delta t = -\left( \ln \frac{lc - x}{lc - x_o} \right) \cdot \frac{V}{Q}. \quad (6)$$

Hence, the change in time  $\Delta t$  for a test period is a function of the initial and final concentration of the tracer gas  $x_o$  and  $x$ , respectively, inside the enclosure, the volume  $V$  of the enclosure, the total ventilation system air quantity  $Q$ , the percentage of air leaked through the ventilation system  $l$ , and the concentration of tracer gas  $c$  outside the enclosure. As described below, equation 6 provides the basis for a timed performance test for determining whether the leakage of the cab 12 meets or exceeds a specified minimum allowable leakage.

In one embodiment of such a test, for example, a gas monitor is used to measure the concentration of tracer gas  $c$  outside the cab 12 and the initial

concentration of tracer gas  $x_0$  inside the cab 12. For a specified leakage  $l$ , and assuming a filter efficiency of 100%, the final or minimum concentration of tracer gas  $x$  inside the cab 12 is the product of the leakage  $l$  and the concentration of tracer gas  $c$  outside the cab 12 (i.e.,  $l \cdot c$ ). If the filter efficiency is less than 100%, the product  $l \cdot c$  is added to the expected leakage through the filter 16 (i.e., the penetration of tracer gas through the filter 16) to determine the final or minimum concentration of tracer gas  $x$  inside the cab 12. The value for the volume  $V$  in equation 6 can be measured or obtained from the manufacturer of the cab 12. The value for  $Q$  can be measured using a conventional air flow meter or by measuring the differential pressure across the filter and translating the differential pressure into the air quantity  $Q$ , as further described below. Substituting these values into equation 6, the time  $\Delta t$  required for the concentration of tracer gas inside the cab 12 to reduce to the minimum level  $x$  for the specified leakage  $l$  is calculated. The change in time  $\Delta t$  provides a reference value for determining whether the actual leakage of the cab 12 is equal to or less than the specified minimum leakage for the cab 12.

After calculating the time  $\Delta t$ , the cab 12 is tested to measure the actual time required for the concentration of tracer gas inside the cab 12 to reach the minimum level  $x$ . If the measured change in time is less than the change in time determined mathematically, then the actual leakage of the cab 12 is less than the specified leakage  $l$ . On the other hand, if the measured change is greater than the change in time determined mathematically, then the actual leakage of the cab 12 is greater than the specified leakage  $l$ . If it is determined that the actual leakage is not acceptable, the ventilation system 10 can be further tested to identify the portions of the ventilation system 10 causing the leaks, as described above, so that those portions can be repaired and/or replaced as necessary.

In some cases, the filtered air quantity  $Q$  for a particular enclosure may not be easily determined with a conventional air flow meter. Instead of using an air flow meter to determine the value of  $Q$  for any enclosure, a  $\Delta p$  (differential pressure) v.  $Q$  flowchart can be generated for a particular filter 16 for relating  $\Delta p$  to  $Q$  for that filter. Thus, the amount of filtered air flowing into an enclosure can be determined by measuring the differential pressure across the filter 16 and translating

the differential pressure measurement into a filtered air quantity measurement using the flowchart.

The methods and systems described herein can be used to test the integrity of a seal or gasket of a filter used in a ventilation system. In one embodiment, for example, a test filter capable of filtering a tracer gas is installed in the ventilation system of a test stand, and a leak test is performed by flowing outside air through the ventilation system and into the enclosure of the test stand. Since the ventilation system, other than the seal of the filter, is essentially leak-free, the presence of tracer gas inside the enclosure indicates the gasket is not sufficiently sealing the filter. Thus, in this embodiment, a leak test performed on the ventilation system tests the ability of the gasket to provide a fluid-tight seal for the filter.

### Examples

#### Example 1

This example illustrates the application of a timed performance test for determining whether the leakage of a cab meets or exceeds a specified minimum allowable leakage. An enclosure having a volume ( $V$ ) of 52.5 ft<sup>3</sup> and a ventilation system operable to produce an airflow rate ( $Q$ ) of 25 cfm is tested using carbon dioxide as the tracer gas. The carbon dioxide concentration ( $c$ ) measured outside the enclosure is 425 ppm, and the initial carbon dioxide concentration ( $x_0$ ) measured inside the enclosure is 394 ppm. Assuming a filter efficiency of 100%, the final carbon dioxide concentration ( $x$ ) inside the enclosure at a leakage ( $I$ ) of 2% will be 8.5 ppm.

Equation 6 is based on the natural logarithm of the concentration ratio  $(Ic - x)/(Ic - x_0)$ , which ranges from negative to positive infinity. Thus, if the exact limit of the final inside cab concentration ( $x$ ) is used in equation 6, the natural logarithm of the concentration ratio goes off to negative infinity and the time ( $t$ ) goes off to infinity. Accordingly, for a viable application of equation 6, the final concentration ( $x$ ) is rounded up, such as to the nearest tenth or whole number. In the present example, the final carbon dioxide concentration ( $x$ ), which is 8.5 ppm, is rounded up to the nearest whole number, which is 9 ppm.

Applying equation 6, the concentration of carbon dioxide enclosure inside the enclosure should reduce to 9 ppm in 14 minutes for a 2% leakage. During

testing, the concentration of carbon dioxide inside the enclosure reduced to 9 ppm in less than 14 minutes, indicating that the actual leakage of the ventilation system is less than 2%. The ventilation system in this example therefore would provide at least a 50:1 protection factor for the occupant of the enclosure. On the other hand, 5 had the time for the concentration of carbon dioxide to reduce to 9 ppm exceeded 14 minutes, or if the concentration of carbon dioxide could not be reduced to 9 ppm, then the actual leakage would be more than 2%.

## 10      Example 2

This example demonstrates the performance of one embodiment of a carbon dioxide filter having a rectangular housing, such as shown in FIGS. 2 and 3. The filter includes about 6 lbs. of soda lime (Puritan Bennett Corp., Pleasanton, CA) retained between two electrostatic filter elements. The soda lime comprises about 15 70% calcium hydroxide (although other formulations also may be used). The housing has a length L (FIG. 2) measured between the side walls of the housing of about 16 inches and a height H (FIG. 2) measured between the top and bottom walls of the housing of about 6 inches. The bed of soda lime in the filter has a depth, or thickness, measured in the direction of flow of about 2.19 inches.

20      Table 1 below illustrates the performance of the filter for airflows of about 15.7 cfm and 24.8 cfm into a simulated cab test stand having an interior cab volume of about 52.3 ft<sup>3</sup>. As shown in Table 1, the filter was 100% efficient at 15.7 cfm and 24.8 cfm, and achieved 0 ppm of carbon dioxide inside the cab within 16 minutes at 15.7 cfm and within 4.3 minutes at 24.8 cfm.

	Cab Airflow 15.7 cfm	Cab Airflow 24.8 cfm
Time (min)	Inside Conc. (ppm)	Inside Conc. (ppm)
0.0	389	35
1.0	402	11
2.0	369	15
3.0	305	16
4.0	242	16
5.0	224	0
6.0	183	
7.0	121	
8.0	75	
9.0	66	
10.0	52	
11.0	28	
12.0	20	
13.0	8	
14.0	8	
15.0	12	
15.5	3	
16.0	0	

Table 1

Example 3

This example demonstrates the performance of a carbon dioxide filter having a cylindrical housing, such as shown in FIGS. 4 and 5. The filter in this example has an outer diameter of about 10.75 inches and a length of about 7 inches, and contains about 10.3 lbs. of soda lime (Puritan Bennett Corp.) retained between two electrostatic filter elements. Table 2 below shows the performance of this filter for an airflow of about 24.8-25 cfm into the 52.3 ft<sup>3</sup> cab test stand. As shown in Table 2, the filter was 100% efficient and achieved 0 ppm of carbon dioxide inside the cab within 15 minutes of operation.

Time (min)	Inside Conc. (ppm)	Outside Conc. (ppm)
0.0	610	558
1.0	582	564
2.0	502	568
3.0	352	576
4.0	228	580
5.0	156	586
6.0	120	593
7.0	57	601
8.0	38	610
9.0	37	606
10.0	41	602
11.0	36	593
12.0	31	592
13.0	27	593
14.0	16	594
15.0	0	589

Table 2 (Cab Airflow = 24.8-25.0 cfm)

Example 4

5 Another example of a filter has a generally rectangular housing, such as shown in FIGS. 2 and 3, that measures about 16 inches in length and about 6 inches in height. The filter is filled with about 5.64 lbs. of Drägersorb® 400 soda lime (Draeger Safety, Inc. of Pittsburgh, PA). The bed of soda lime has a depth measured in the direction of flow of about 2.19 inches. Table 3a below illustrates the

10 performance of the filter when used to filter the air flowing into the 52.3 ft<sup>3</sup> cab test stand at a flow rate of about 24.9 cfm. As shown in Table 3a, the filter was 100% efficient at 24.9 cfm and achieved 0 ppm of carbon dioxide inside the cab within 12 minutes.

The same filter was then used to filter air flowing into the test stand at a flow

15 rate of about 40 cfm. The flow rate was reduced to about 35 cfm after about 15 minutes of operation and then to about 25.4 cfm after about 23 minutes of operation. The performance of the filter is summarized in Table 3b, which shows that the filter was about 95% efficient at 40 cfm and 100% efficient when the air flow was reduced to 25.4 cfm.

Time (min)	Inside Conc. (ppm)	Outside Conc. (ppm)
0.0	612	590
1.0	568	594
2.0	407	579
3.0	267	614
4.0	200	628
5.0	153	629
6.0	110	627
7.0	77	631
8.0	45	631
9.0	24	630
10.0	5	631
11.0	1	628
12.0	0	642
13.0	0	632
14.0	0	631
15.0	0	628

Table 3a (Cab airflow = 24.9 cfm)

Time (min)	Inside Conc. (ppm)	Outside Conc. (ppm)	Time (min)	Inside Conc. (ppm)	Outside Conc. (ppm)
0.0	624	608	18.0	22	513
1.0	570	577	19.0	18	538
2.0	333	597	20.0	19	514
3.0	184	547	23.0	13	533
4.0	124	571	25.0	8	542
5.0	85	565	26.0	2	523
6.0	66	563	27.0	3	524
7.0	46	550	28.0	6	555
8.0	40	542	29.0	1	526
9.0	32	546	30.0	2	573
10.0	28	506	32.0	0	542
11.0	21	511	35.0	0	519
12.0	21	544	37.8	0	516
13.0	19	511	39.0	0	499
14.0	17	521	40.0	3	531
15.0	24	516	44	0	505
16.0	26	525			
17.0	25	520			

Table 3b (Cab airflow = 40 cfm at  $0 \leq t \leq 15$ ; 35 cfm at  $16 \leq t \leq 20$ ; and 25.4 cfm at  $23 \leq t \leq 44$ )

Example 5

This example demonstrates the performance of a carbon dioxide filter comprising a John Deere model JD60R filter housing (John Deere Co., Moline, IL) packed with about 7.86 lbs. of Drägersorb® 400 soda lime. The filter was initially used to filter the air flow into a John Deere model 7800 tractor cab. Table 4 below shows the carbon dioxide concentration inside and outside the cab while the cab fan was operated at its highest speed level (which is the fourth speed level of the fan) and the second highest speed level (which is the third speed level of the fan). The speed of the fan was reduced from the fourth speed level to the third speed level after 20 minutes of operation. The filter achieved 0 ppm of carbon dioxide inside the cab after about 9 minutes at the third speed level of the fan.

Time (min)	Inside Conc. (ppm)	Outside Conc. (ppm)	Time (min)	Inside Conc. (ppm)	Outside Conc. (ppm)
0.0	461	334	18.0	7	335
1.0	384	363	19.0	11	324
2.0	306	373	20.0	15	329
3.0	209	353	21.0	45	333
4.0	159	335	22.0	69	331
5.0	106	360	23.0	77	337
6.0	71	340	24.0	59	339
7.0	63	340	25.0	50	334
8.0	45	346	26.0	36	311
9.0	36	344	27.0	21	320
10.0	38	347	28.0	16	324
11.0	36	321	29.0	7	330
12.0	23	344	29.1	0	338
13.0	13	340			
14.0	12	339			
15.0	6	329			
16.0	6	326			
17.0	6	334			

Table 4

The filter was then used to filter the air flow into the 52.3 ft<sup>3</sup> cab test stand. Table 5 below shows the carbon dioxide concentration inside and outside of the cab



at a flow rate of 47.7 cfm. As shown the filter was 100% efficient at 47.7 cfm and achieved 0 ppm of carbon dioxide inside the cab in about 7 minutes.

Time (min)	Inside Conc. (ppm)	Outside Conc. (ppm)
0.0	484	321
1.0	354	337
2.0	209	339
3.0	106	343
4.0	63	332
5.0	18	329
6.0	12	321
7.0	0	308
8.0	0	309
9.0	0	318
10.0	0	308

Table 5 (Cab airflow = 47.7 cfm)

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The present invention has been shown in the described embodiments for illustrative purposes only. The present invention may be subject to many modifications and changes without departing from the spirit or essential characteristics thereof. We therefore claim as our invention all such modifications  
10 as come within the spirit and scope of the following claims.